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Letter

On the Hubble expansion in a Big Bang quantum cosmology

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ABSTRACT

The Hubble expansion of the Universe is considered in the classical limit of a Big Bang quantum cosmology. In an IR-consistent coupling to the bare cosmological constant, we infer a dark energy as a relic of the Big Bang by loss of time-translation invariance on a Hubble time-scale. This dark energy is identified with the trace J of the Schouten tensor permitting an analytic solution $H(z)$. Anchored by the *Baryonic Accoustic Oscillations*, JCDM predicts a Hubble constant $H_0 = \sqrt{6/5}\,H_0^\Lambda$ alleviating H_0-tension between the Local Distance Ladder and H_0^Λ in ΛCDM, whose dark energy Λ is a constant. Emulated by $w(a)\Lambda$CDM, a CAMB analysis shows a JCDM fit to the *Planck* 2018 C_l^{TT} power spectrum on par with ΛCDM with small positive curvature consistent with *Planck*-ΛCDM with no extra relativistic degrees of freedom. In late-time cosmology, JCDM is also consistent with the BAO recently measured by DESI. JCDM offers a novel framework to address H_0-tension, predicting background quantities consistent with the uncertainties in BAO measurements and early-Universe observations. It predicts a deceleration parameter $q_0 \simeq -1$, that may be tested with upcoming low-redshift galaxy surveys.

1. Introduction

From dawn at the Big Bang to the present epoch, the Universe has been expanding for a Hubble time with the formation of the large-scale structure in galaxies on smaller scales. This process evolves in weak gravitation largely at the cosmological de Sitter scale of acceleration $a_{dS} = cH$, where c is the velocity of light and H is the Hubble rate of expansion. By the Copernicus principle, the Universe on the largest scales is believed to be homogeneous and isotropic, described in the Friedmann-Lemaître-Robertson-Walker (FLRW) line-element (Sandage, 1961)

$$ds^2 = a^2\eta_{ab}dx^a dx^b \tag{1}$$

by conformal scaling a of the Minkowski metric η_{ab}. Equivalently, $ds^2 = -c^2dt^2 + a(t)^2\left(dx^2+dy^2+dz^2\right)$ expresses $H = \dot a/a$ as a function of cosmic time t with Hubble radius $R_H = c/H$ and deceleration parameter $q = -a\ddot a/\dot a^2$. The latter equals $q(z) = -1 + (1+z)H^{-1}H'$ in terms of redshift z, where $a/a_0 = 1/(1+z)$ normalized to a_0 today (Sandage, 1961).

Crucially, the Hubble parameter $H_0 = H(0)$ points to a Big Bang, a time H_0^{-1} in the past (Aghanim et al., 2020). While a theory of quantum cosmology remains elusive (Agrawal et al., 2018), this Big Bang breaks time-translation invariance that, on a Hubble time, introduces a small energy scale $\epsilon \sim H\hbar$ per degree of freedom (van Putten, 2020). The dimension of phase space within a radius $r \le R_H$ is finite by the Bekenstein bound $N = A_p/4$ by the area $A_p = 4\pi r^2/l_p^2$ in Planck units, $l_p = \sqrt{G\hbar/c^3}$ (Bekenstein, 1981), given Newton's constant G and Planck's constant $\hbar$. Including a factor of $1/2\pi$, preserving consistency with the first law of thermodynamics (Padmanabhan, 2003; van Putten, 2024c), $\epsilon = H\hbar/2\pi$ (Gibbons and Hawking, 1977) is an energy scale of the vacuum of de Sitter space, pointing to a relic heat of the Big Bang

$$Q \simeq N\epsilon \tag{2}$$

distinct from the semi-classical UV-catastrophe (Weinberg, 1989). The corresponding energy density $\rho_c = 3Q/4\pi R_H^3 = 3H^2c^2/8\pi G$ reaches closure density in the limit of a de Sitter universe.

In the face of a cosmological horizon $\mathcal{H}$ at R_H, therefore, the cosmological vacuum assumes thermodynamic properties by (2) very similar to those of black holes (Gibbons and Hawking, 1977), satisfying $Q \equiv Mc^2$ by Clausius' integral for a Schwarzschild black hole of mass M (e.g. (van Putten, 2024a)). Accordingly, the vacuum of a Big Bang quantum cosmology is distinct from that of general relativity (GR), which assumes the asymptotic null-infinity $\mathcal{N}$ of Minkowski spacetime. Given $\mathcal{N}$, the strong field limit of GR notably predicts black holes including Kerr black holes (Kerr, 2023) and their evaporation by accompanying outgoing radiation conditions (Hawking, 1975; van Putten, 2024a). Yet, the same $\mathcal{N}$ is inconsistent with $\mathcal{H}$ in (1), prohibiting its direct application to weak gravitation on the scale of a_{dS}.

As a result, FLRW cosmologies (1) have a non-classical vacuum (2), arising from an infinite cosmological redshift of $\mathcal{H}$ in (1) rather than the

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zero redshift of $\mathcal{N}$ in Minkowski spacetime. We hereby anticipate a Hubble expansion $H(z)$ driven by a dark energy (2) distinct from the case of a constant dark energy, known as ΛCDM (Ade et al., 2014; Aghanim et al., 2020; Tristam et al., 2024).

2. An IR-consistent cosmological vacuum

As a first step, we recall the bare cosmological constant $\Lambda_0 = 8\pi G c^{-4}\rho_0$ of quantum field theory inferred from the Planck energy density $\rho_0 = \hbar c/l_p^4$ (Zeldovich, 1967; Weinberg, 1989). This $\Lambda_0 \sim 1/\hbar$ is UV-divergent in $1/\hbar$ - a *primitive* necessitating an IR-consistent coupling to spacetime satisfying aforementioned Bekenstein bound (van Putten, 2024c). The result is expected to be dynamical by the swampland conjectures (Agrawal et al., 2018). A similar primitive is encountered in coupling matter by position to spacetime (van Putten, 2024c).

To this end, we consider (1) in spherical coordinates with radial coordinate r and the reciprocal $\alpha_p \sim \hbar$ of $A_p = 4\pi r^2/l_p^2$,

$$\alpha_p A_p = 1, \tag{3}$$

over $0 \le r \le R_H$. For $r < R_H$, α_p provides an IR-consistent coupling of matter to spacetime (van Putten, 2024c). In a unified treatment, the visible Universe covered by $r = R_H$ leaves

$$\Lambda = \alpha_p \Lambda_0 = 2H^2/c^2. \tag{4}$$

This outcome is less than limit $\rho_\Lambda = \rho_c$ in de Sitter space in keeping with aforementioned Bekenstein bound. For a three-flat universe (1), this points to an additional distribution of dark matter. Excluding the de Sitter limit as a physical state of the Universe, it further points to a dynamical dark energy anticipated by the swampland conjectures.

By the above, therefore, the vacuum of a Big Bang cosmology (1) is inequivalent to that of GR, and hence ΛCDM. By IR-consistent coupling to gravitation, we anticipate a dynamical dark energy (4). We formalize (4) by a path integral formulation gauged in global phase by $\mathcal{H}$ (van Putten, 2020, 2021).

This new approach on the Hubble expansion of a non-classical cosmological vacuum appears opportune in light of the H_0-tension between the Local Distance Ladder and standard ΛCDM (Aghanim et al., 2020; Di Valentino et al., 2021; Riess et al., 1998; Weinberg et al., 2022; Riess et al., 2022).

3. Dark energy from first principles

An exact expression for Λ in (4) derives from a path integral formulation with gauged propagator $e^{i(\Phi-\Phi_0)}$ (van Putten, 2020), where $\Phi = S/\hbar$ for an action S and Φ_0 is a global phase reference. In the face of $\mathcal{H}$ rather than $\mathcal{N}$, $\Phi_0 = \Phi_0[\mathcal{H}]$ represents a boundary term $S_0 = \hbar\Phi_0[\mathcal{H}]$ in the total action. In a Big Bang cosmology (1), Φ_0 is inherently dynamic, taking us away from de Sitter as anticipated above. To proceed, S_0 can be absorbed in S by a Lagrangian density 2Λ as $\Lambda = \lambda R$ - a multiple of the Ricci scalar tensor as a function of the running Friedmann scale a. In what follows, we consider $\lambda = 1/6$ inferred from thermodynamic arguments (van Putten, 2015). In four dimensions, we recognize $J = R/6$ as the trace of the Schouten tensor known for conformal symmetries (Schouten, 2011). That is,

$$\Lambda = J, \tag{5}$$

where $J \equiv (1-q)H^2/c^2$ in canonical quantities (H, q) (van Putten, 2015). This recovers (4) when $q = -1$ and $\Lambda = 0$ in the radiation-dominated limit ($q = 1$) prior to the BAO. By (5), JCDM is inequivalent to ΛCDM, which assumes Λ to be frozen.

4. Hubble expansion of JCDM

With (5), we obtain an analytic solution $H(z) = H_0 h(z)$ (van Putten, 2021),

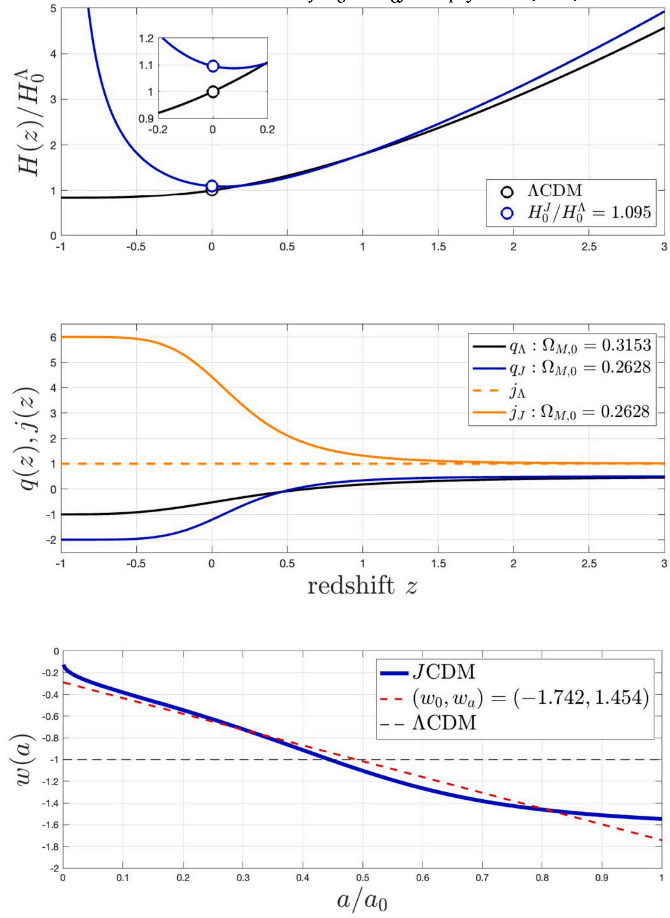

Fig. 1. (Top panel.) $H(z)$ normalized to $H_0^\Lambda(z)$ of ΛCDM, highlighting sensitivity of H_0 in extrapolating low-z data from the Local Distance Ladder data to $z = 0$. This extrapolation is sensitive to the shape of the graph, determined by the equation of state parameter w of dark energy relating pressure and energy $p_\Lambda = w\rho_\Lambda$. Here, $w = (2q-1)/(1-q)$ for JCDM (van Putten, 2017; Colgáin et al., 2019) and $w \equiv -1$ for ΛCDM. (Middle panel.) JCDM departs from ΛCDM noticeably at late times. (Lower panel.) $H(z)$ in JCDM can be emulated by the Hubble expansion of $w(a)$ΛCDM with corresponding nonlinear function $w(a)$ (blue solid curve). For illustrative purposes, included is the linear trend line (dashed red line) $w = w_0 + w_a(1-a)$.

$$h(z) = \frac{\sqrt{1 + \frac{3}{2}\Omega_{K,0}Z_4(z) + \frac{6}{5}\Omega_{M,0}Z_5(z) + \Omega_{r,0}Z_6(z)}}{1+z}, \tag{6}$$

where $Z_n = (1+z)^n - 1$ $(n \ge 1)$. Here, $\Omega_{M,0}$ and $\Omega_{r,0}$ denote the dimensionless densities of matter and, respectively, radiation at $z = 0$, normalized to the present closure density $\rho_{c,0}$. $\Omega_{K,0} < 0\,(>0)$ is the density of positive (negative) curvature. In the same notion, ΛCDM satisfies $H(z) = H_0 E(z)$ with $E(z) = \sqrt{1 + \Omega_{K,0}Z_2(z) + \Omega_{M,0}Z_3(z) + \Omega_{r,0}Z_4(z)}$.

At late times in JCDM, when radiation can be neglected, matter and dark energy densities satisfy $\Omega_M = \frac{1}{3}(q+2)$ and, respectively, $\Omega_\Lambda = \frac{1}{3}(1-q)$ and $q^\Lambda = \frac{3}{2}\Omega_M^\Lambda - 1$ (van Putten, 2021). The dark energy equation of state between pressure and energy, $p_\Lambda = w\rho_\Lambda$, satisfies $w = (2q-1)/(1-q)$ distinct from $w \equiv -1$ in ΛCDM (van Putten, 2017; Colgáin et al., 2019). In the matter-dominated era ($q = 1/2$, $w = 0$), $\Omega_M = 5/6$ and $\Omega_\Lambda = 1/6$ conspire to preserve closure density at zero total pressure. This reduces Ω_M partaking in large-scale structure formation in JCDM to 5/6 times the matter density in ΛCDM, i.e.:

$$\Omega_{M,0} = \frac{5}{6}\Omega_{M,0}^\Lambda. \tag{7}$$

Fig. 1 shows the late-time Hubble expansion in JCDM alongside ΛCDM. By the distinct slope and curvature in the two graphs at the

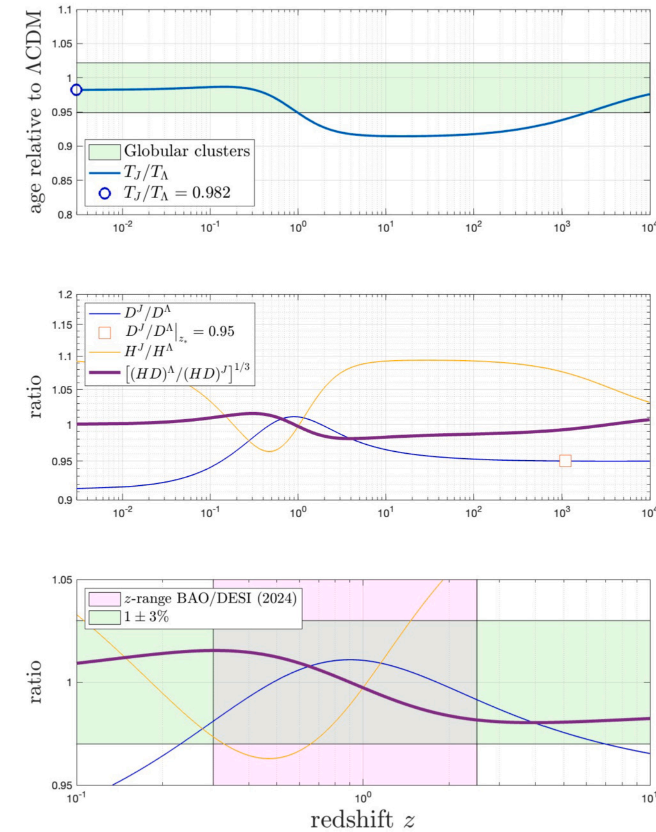

Fig. 2. (Upper panel.) The age T_J of the Universe in JCDM relative to T_Λ in ΛCDM, against the astronomical age of the Universe inferred from the ages of the oldest stars in Globular Clusters (Valcin et al., 2020). In JCDM, the Universe is slightly younger than in ΛCDM by a mere 1.8% (open circle). (Middle panel.) Shown are ratios of canonical quantities between JCDM and ΛCDM, namely $D_A^J/D_A^\Lambda = D_L^J/D_L^\Lambda \equiv D^J/D^\Lambda$ of angular distances $D_A = D_M/(1+z)$ and luminosity distances $D_L = (1+z)D_M$ in terms of the comoving distance D_M (blue curve), of the Hubble expansion (yellow curve) and the cube root of HD relevant to the recent DESI measurements of the BAO (Adame et al., 2024) by (12). (Lower panel.) Zoom-in of middle panel, highlighting consistency with *Planck*-ΛCDM within 2% (green strip), consistent with a few percent uncertainty in DESI measurements.

present epoch, we anticipate a tension in H_0 when extrapolating $H(z)$-data over $z>0$ from the Local Distance Ladder to $z=0$ (Abchouyeh and van Putten, 2021). This distinction is seen to be at late times $z \lesssim 1$ by $j \equiv \dddot{a}a^2/\dot{a}^3$ $\left(j(z) = q(z)(2q(z)+1) + (1+z)q'(z)\right)$ with the property that $j \equiv 1$ for ΛCDM. Due to this late-time transition, the age of the universe in JCDM remains close to that of ΛCDM shown in Fig. 2, alongside the angular and luminosity distances relative to ΛCDM.

5. Anchoring in the BAO

In the radiation dominated epoch, JCDM and ΛCDM share the asymptotic expansion $H(z) \sim H_0\sqrt{\Omega_{r,0}}(1+z)^2$. This suggests anchoring JCDM in early cosmology by the sound horizon in the surface of last scattering (SLS) at redshift $z_* \simeq 1090$ according to the *Planck*-ΛCDM analysis of the CMB:

$$\theta_* = \theta_*^\Lambda, \tag{8}$$

where the superscript J on the left hand-side is understood. Here, θ_* defined by the angle (Ade et al., 2014; Aghanim et al., 2020; Tristam et al., 2024)

$$100\theta_* \equiv \frac{r_*}{D_*} = (1.04092 \pm 0.00030)\ \mathrm{rad}, \tag{9}$$

that determines the location of the main peak in the power spectrum of the CMB. It represents $\theta_* = r_*/D_*$ in terms of the radius $r_* = \int_{z_*}^\infty c_s dz/H(z)$ and the comoving distance $D_* = c\int_0^{z_*} dz/H(z)$ (Aghanim et al., 2020; Jedamzik et al., 2021; Pitrou and Uzan, 2024). Crucially, $c_s = 1/\sqrt{3(1+R)}$ is the sound speed in the primordial baryon-poor fluid, determined by the baryon-to-photon density ratio ρ_b/ρ_γ, where $R = 3\rho_b/4\rho_\gamma$.

To this end, we let (6) preserve the *Planck* un-normalized dimensionless densities $\Omega_{M,0}h^2 = 0.1431$ and $\Omega_{r,0}h^2 = 2.4661\times 10^{-5}$ (by the CMB temperature today) in $h = H_0/100\,\mathrm{km\,s^{-1}Mpc^{-1}}$. With (7), the first predicts the J/Λ-scaling

$$H_0 = \sqrt{\frac{6}{5}}H_0^\Lambda \tag{10}$$

and $q_0 = \left(5q_0^\Lambda - 1\right)/3$. By (9)-(10), (7) preserves the matter density $\rho_{M,0}$ of ΛCDM: $\Omega_{M,0}$ appears lower in the face of $\rho_c = (6/5)\rho_c^\Lambda$. By (10), the radiation-to-matter density ratio satisfies $\eta = \Omega_{r,0}h^2/\Omega_{M,0}h^2 = (1.7238 \pm 0.03)\times 10^{-4}$.

Anchored by (8), JCDM preserves θ_*^Λ of three-flat ΛCDM at $N_{\rm eff}^\Lambda = 3.046$. In keeping with a direct confrontation between JCDM and ΛCDM, both are here considered with essentially zero curvature. In a CMB-only analysis, the original *Planck*-ΛCDM analysis of the CMB suggests a slight positive curvature, the value of which varies appreciably with choice of data combination. While complex, this is now recognized to be largely a lensing anomaly, resolved to some extent in subsequent revised *Planck* analyses (Di Valentino et al., 2020; Tristam et al., 2024). For instance, $\Omega_k < -0.007$ in TT, TW, EE+lowE in (Aghanim et al., 2020). Numerical root finding of (8) shows the correlation $\Delta N_{\rm eff} \simeq 0.2566 + 0.1640\times\left(100\Omega_K\right)$, according to which $0.1 < \Delta N_{\rm eff} < 0.26$ for $-1 \le 100\Omega_K \le 0$ in JCDM. In particular, a fiducial value $\Omega_k = -0.007$ yields $\Delta N_{eff} = 0.1418$ for JCDM, i.e., $N_{eff} = 3.1878$. This ΔN_{eff} is well within the uncertainty of CMB-only *Planck* ΛCDM-parameter estimates (Ade et al., 2014; Aghanim et al., 2020; Tristam et al., 2024) and the corresponding N_{eff} is consistent with the DESI estimate $N_{eff} = 3.20 \pm 0.19$ (Adame et al., 2024). This sensitivity analysis on (8) indicates insignificant deviations from the concordance model of a flat cosmology with no need for extra relativistic degrees of freedom.

6. Confrontation with the local distance ladder

By (7), (10) and anchored by (8)-(9), JCDM predicts $h \simeq 0.74$ with $\Omega_{M,0} \simeq 0.26$. JCDM hereby resolves the H_0-tension between the BAO and late-time cosmology in ΛCDM with negligible change in the age of the Universe (Fig. 2).

Similar but less pronounced departures from ΛCDM are seen in a minimal extension of CDM (Pitrou and Uzan, 2024), predicting a low matter density $\Omega_{M,0} \simeq 0.267$ similar to ours with, however, a limited increase in the Hubble constant to $h = 0.7187$.

Table 1 and Fig. 3 summarize the outcome of the confrontation of JCDM anchored in the BAO with late-time cosmology probed by the Local Distance Ladder.

7. Planck CMB power spectrum

With J/Λ-scaling (7) and (10) and BAO anchoring (9), the CMB power spectrum in JCDM is expected to closely follow that of *Planck*. Fig. 4 shows a confrontation of JCDM and ΛCDM with binned D_l^{TT} data of the *Planck* CMB power spectrum (Planck Public Data Release 3, 2018) with small positive curvature consistent with *Planck*-ΛCDM (Ade et al., 2014; Aghanim et al., 2020; Tristam et al., 2024). Fig. 4 is calculated by CAMB (Lewis et al., 2000) applied to $w(a)\Lambda$CDM emulating JCDM, using the nonlinear curve $w(a)$ (blue curve in Fig. 1) tabulated over 5000 data points covering the interval $0 \le a \le 1$.

For large scales, the JCDM power spectrum drops slightly below that of ΛCDM. This is a familiar feature of models beyond ΛCDM seen, e.g.,

Table 1
JCDM parameter estimates versus *Planck*, the Local Distance Ladder (LDL) by the SH0ES collaboration (Riess et al., 2022) and tabulated $H(z)$ data of Farooq et al. (2017). Results are expressed by (H_0, q_0), including $\Omega_{M,0}$ except in model-independent analyses of the LDL. Results by J/Λ-scaling are based on anchoring in the BAO (8), and, independently, from LDL. All results refer to three-flat cosmologies. S_8 estimates derive from CAMB Lewis et al. (2000). H_0 is in km s^{-1}Mpc^{-1} and T_U is in Gyr.

	Planck/CMB[a]	J/Λ−scaling/BAO[b]	JCDM/LDL[c]	Cubic/LDL[d]	SH0ES/LDL[e]
H_0	67.36 ± 0.54	73.79 ± 0.59	74.9 ± 2.60	74.44 ± 4.9	73.04 ± 1.04
q_0	-0.5273 ± 0.011	-1.21 ± 0.014	-1.18 ± 0.084	-1.17 ± 0.34	-1.08 ± 0.29
$\Omega_{M,0}$	0.3153 ± 0.0073	0.2628 ± 0.0061	0.2719 ± 0.028	–	–
S_8	0.832 ± 0.013	0.756 ± 0.012			
T_U	13.797 ± 0.023	13.44 ± 0.022			

[a] *Planck*, Eq. (27) of Aghanim et al. (2020). [b] Scaling relations (7)-(10). [c] JCDM fit (van Putten, 2017) to tabulated $H(z)$ data of Farooq et al. (2017). [d] Cubic polynomial fit (van Putten, 2017) to tabulated $H(z)$ data of Farooq et al. (2017). [e] H_0 from Riess et al. (2022) and q_0 from Camarena and Marra (2020).

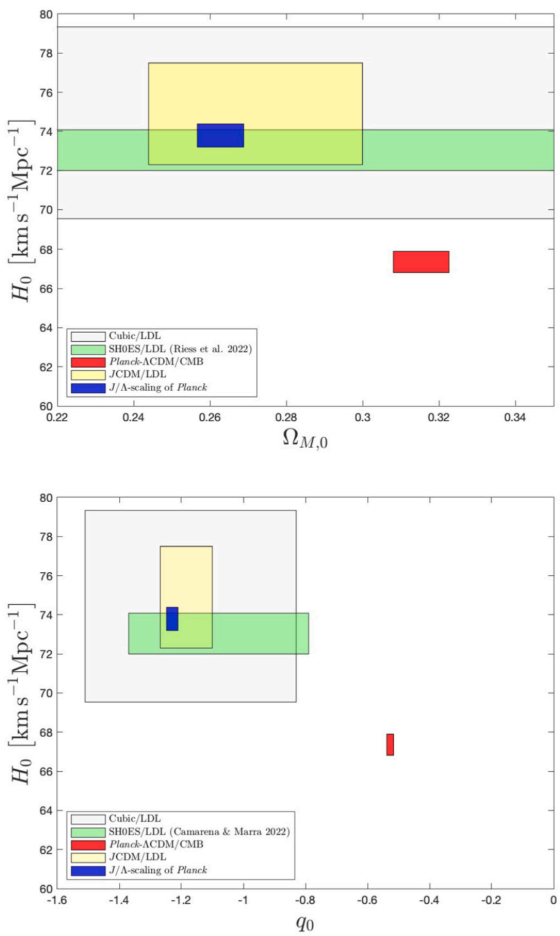

Fig. 3. (Top panel.) $(\Omega_{M,0}, H_0)$-plane of Table 1, showing *Planck*-ΛCDM (red), SH0ES/LDL (green), JCDM fit to the LDL (yellow) and J/Λ-scaling of *Planck* (blue) following (7)-(10) against a model-agnostic background provided by a cubic polynomial fit to LDL (light gray). (Bottom panel.) The same shown in the (q_0, H_0)-plane.

in quintom cosmology (Cai et al., 2010), which is allowed given the relatively large cosmic variance at low l (Roland de Putter et al., 2010; Ade et al., 2014).

On smaller scales, the matter clustering amplitude σ_8 on the scale of $8h^{-1}$ Mpc is commonly expressed by the quantity $S_8 = \sigma_8\sqrt{\Omega_{M,0}/0.3}$ (Aghanim et al., 2020; Di Valentino et al., 2021; Jedamzik et al., 2021). Preserving the *Planck*-ΛCDM parameter $\Omega_{M,0}h^2$, it satisfies

$$S_8 \sim \sigma_8 h^{-1}. \tag{11}$$

While σ_8 slightly increases with h, S_8 hereby reduces by about 7% in response to (7) (Table 1).

8. Conclusions

JCDM models the Hubble expansion of a non-classical vacuum of a Big Bang cosmology by first principles with no variation of fundamental constants (van Putten, 2024d). Its origin is an IR-consistent coupling of Λ_0 to spacetime (3)-(5) in keeping with the Bekenstein bound (Bekenstein, 1981) and formalized in JCDM based on a path integral formulation of (1) with gauged global phase.

JCDM predicts H_0 to be larger than H_0^Λ of ΛCDM by a factor of $\sqrt{6/5}$ and reduced matter density $\Omega_{M,0}$ (7) and (10). This J/Λ-scaling identifies the H_0-tension between the Local Distance Ladder and *Planck*-ΛCDM with relic heat in the vacuum, in a Hubble expansion anchored in the BAO of the *Planck* power spectrum of the CMB with reduced S_8 (Fig. 4, Table 1).

The dynamical dark energy (5) has a simple meaning in a finite content in heat: a relic of the Big Bang breaking time-translation invariance. In turn, (6) satisfies a new symmetry in the form of a T-duality in a and $1/a$ (van Putten, 2021). This derives from the Hamiltonian energy constraint (the first Friedmann equation), now second-order in time by (5) in JCDM rather than first-order in time in ΛCDM, where Λ is assumed to be frozen. This distinction highlights the observational significance of q_0 (Fig. 1).

JCDM alleviates H_0-tension while anchored in the BAO (8)-(9). A further test is provided by the BAO recently measured by DESI over a redshift range $0.3 \lesssim z \lesssim 2.5$ (Adame et al., 2024), reported by the distance ratio $R \equiv D_V/(r_d z^{2/3})$ of the angle-averaged distance $D_V = (zD_M^2 R_H)^{1/3}$ to the sound horizon at the baryon-drag epoch r_d (Jedamzik et al., 2021; Adame et al., 2024). Given the anchor (8), JCDM and *Planck*-ΛCDM results can be compared by the ratio

$$\frac{R^J}{R^\Lambda} = \frac{\left(D_V/r_d\right)^J}{\left(D_V/r_d\right)^\Lambda} = \left(\frac{\beta^\Lambda}{\beta^J}\right)^{1/3}, \tag{12}$$

where $\beta = HD_M/c$ denotes the ratio of transverse to line-of-sight comoving distance (Adame et al., 2024). Fig. 2 (lower panel, purple curve) shows (12) to be within $1 \pm 2\%$. JCDM hereby follows *Planck* to within 2%, consistent with DESI given the uncertainty of $\sim 3\%$ in its BAO data (Adame et al., 2024).

JCDM provides a novel framework for Hubble expansion described by the same six parameters as ΛCDM, and the results based on the constraint (8) and the J/Λ-scaling (7) and (10) of $\Omega_{M,0}$ and, respectively, H_0 suggest it may mitigate tensions between early and late-time cosmology.

As shown in Fig. 3, a definitive discrimination between JCDM and ΛCDM may derive from an accurate measurement of q_0, to effectively

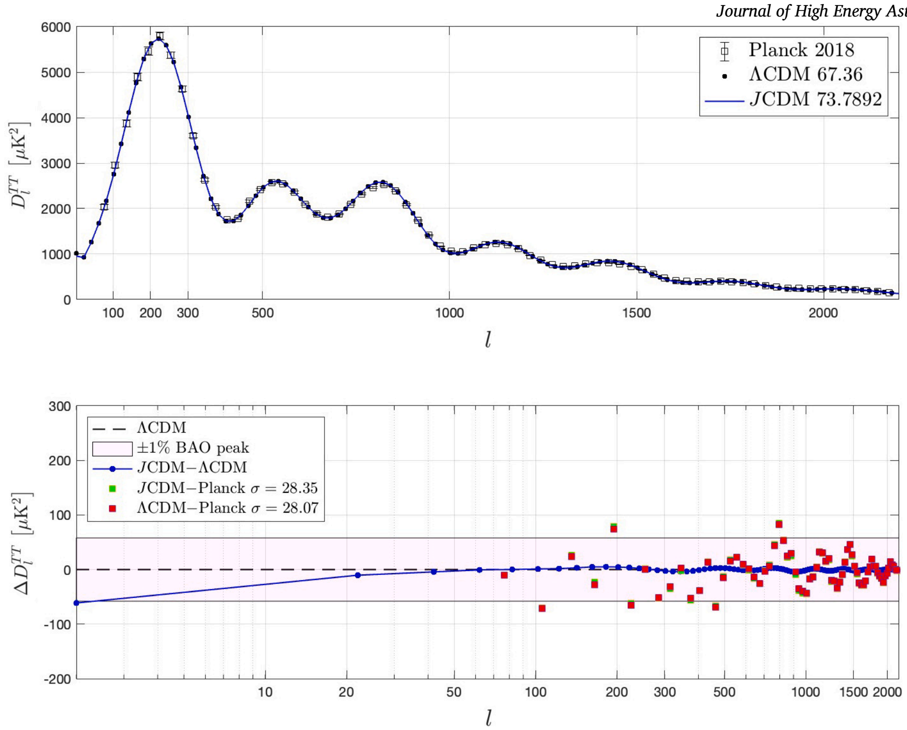

Fig. 4. JCDM and ΛCM model predictions by CAMB to binned *Planck* 2018 TT power spectrum of the CMB upon scaling H_0 by (7) and (10), preserving *Planck* ΛCDM values for all other parameters. JCDM and ΛCDM power spectra are essentially the same except on larger scales ($l \lesssim 30$), where JCDM falls below ΛCDM by about one percent. The σ-values in the legends refer to STDs of JCDM and ΛCDM residuals to the binned *Planck* 2018 data.

determine the order of the first Friedmann equation for a Big Bang cosmology.

Improved observational constraints on late-time cosmology are expected from the BAO in present low-redshift galaxy surveys with the *Dark Energy Survey* (Adame et al., 2024; Abbott et al., 2024) and the recently launched ESA mission *Euclid*. These new probes may confirm a crucial prediction: $q_0 \simeq -1$ in JCDM (Fig. 3) distinct from the ΛCDM value $q_0 \simeq -0.5$ (Camarena and Marra, 2020; van Putten, 2024b). When preserving the fit to the *Planck* power spectrum of the CMB on par with ΛCDM (Fig. 4), a tension in $\left(H_0, q_0\right)$ would represent a definite signature of a non-classical vacuum beyond ΛCDM - beyond the Hamiltonian energy constraint of general relativity. New constraints on the Hubble expansion are further expected from increasingly high-resolution maps of galaxy formation at cosmic dawn by the JWST (Eisenstein et al., 2023) and galaxy rotation curves tracing background cosmology (van Putten, 2024b,c).

CRediT authorship contribution statement

Maurice H.P.M. van Putten: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Only public data is used for the research described in the article.

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